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The Role of Open Innovation in Development of Futuristic Technologies for Carbon Capture in Coal-Fired Power Plants: An Academic Perspective

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Abstract:

Coal is an important fossil fuel resource for electricity generation which also contributes to significant CO_2 emissions. The process of capturing carbon dioxide for utilization and sequestration is an important area of research in this domain. Academia-industry collaborations are playing a significant role in the development of oxy-fired combustion (OFC) and Chemical – looping Combustion (CLC), two technologies under consideration for burning coal in a primarily oxygenated environment to obtain a pure stream of CO_2.

Although OFC and CLC have different technological pathways, they have similarities in their historical development from a laboratory scale to pilot scale. Universities, in collaboration with industry, are continuing to play an important role in the development of these technologies to the pilot scale. Thus OFC and CLC could be visualized as one of the example technological platforms where 'open innovation' is being practiced in the development of carbon capture technologies. Facilitating collaboration in the pursuit of solutions to technologically complex problems can produce benefits such as decreased development time and costs. This paper will discuss the possible pathways which these technologies could undertake based on studies of power plant technologies, environment regulation technology components, and will derive insights from contemporary strategy and innovation literature. The possible challenges expected for carbon capture technologies through the open innovation model in terms of market economics, scale, and technology-enabling legislation which have the potential to frame future scenarios are also highlighted.

Perspective:

The development of suitable technologies for capturing carbon dioxide (i.e. obtaining a high-purity CO_2 stream) emitted from fossil fuel combustion has generated tremendous research interest. The Intergovernmental Panel on Climate Change (IPCC) has estimated the global temperature increase in the coming century to be between 1.8 to 4°C, which is likely attributed to the human-induced greenhouse gas (GHG) concentrations in the atmosphere (Global CCS Institute,2011). In 2010, CO_2 accounted for about 84% of all U.S. greenhouse gas emissions from human activities (US EPA Webpage, 2012).

44.9% of the electricity generated in the United States was derived from coal and peat in 2010 (Edison Electric Institute, 2012). The data on the U.S. energy-related carbon dioxide emissions determined on a sector basis indicates that the combustion of coal contributes to approximately 75% of the CO_2 emissions in the United States resulting from electric power generation (Annual Energy Outlook, 2012). In addition to the addressing the environmental impact of CO_2 emissions, technologies for facilitating capture of carbon dioxide merit potential consideration for generating CO_2 economically. The generated CO_2 could be utilized for injecting into depleted oil wells to recover untapped oil (McConnell, 2012). The pursuit of identifying economic and environmentally friendly technologies for the exploitation and recycling of CO_2 is an emerging area of active research interest (Peters et al., 2012).

Three technology routes are being currently considered for carbon dioxide capture (Markewitz et al., 2012; Riensche et al., 2012). CO_2 can either be captured from the flue gas (i.e. end-products of combustion) termed as ‘post-combustion carbon capture’, or the CO_2 concentration could be enhanced by burning a fuel in an oxygen-rich environment instead of air known as ‘oxy-fuel combustion’. Another class of carbon capture processes exist where CO_2 can be captured before the fuel is burnt called ‘pre-combustion’. The ‘pre-combustion’ carbon capture process is achieved when the solid carbonaceous fuel (e.g. coal, petcoke) is gasified to form syngas which is subsequently converted to a mixture of CO_2 and H_2 by a shift reaction. The CO_2 could be recovered from the CO_2-H_2 gas mixture by a gas separation process. The objective of all the three categories of carbon capture processes (‘post-combustion’, ‘pre-combustion’ and ‘oxy-fuel’) is to obtain a high-purity stream of CO_2 which is suitable for sequestration and subsequent utilization. These processes are energy intensive and the energy requirements are derived from the power plant resulting in an efficiency loss. This efficiency loss for carbon capture processes is currently estimated to be of the order of 10% which is in addition to the efficiency penalty of 1-2% associated with pollutant removal (Riensche et al., 2012).

The subject of carbon capture utilization and sequestration is an extensive area and encompasses various technical, social, economic and ecological aspects. From the perspective of innovation, Johnsson et al. (2009) have reported results of a survey of individuals working in stakeholder organizations indicating widespread belief that technologies based on carbon capture and sequestration have the potential to gain major market entry in the next 10-20 years. Markusson et al. (2012) have developed a framework incorporating technical, economic, financial, political and societal issues associated with innovation for carbon capture and storage(CCS) technologies. In a recent review, Jiang et al. (2012) have highlighted the role of university and industry collaboration on the development of CCS technologies in the UK.

Oxy-fuel Combustion (OFC) and Chemical-looping Combustion (CLC):

The objective of this paper is to facilitate an understanding on the impact of open innovation on the oxy-fuel category of CCS technologies – oxy-fuel combustion (OFC), where oxygen is provided by air separation and chemical-looping combustion (CLC), where a metal oxide is used to supply the oxygen. Open innovation has been defined by Chesbrough as “Open innovation is the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively. [This paradigm] assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as they look to advance their technology."(Chesbrough et al.,2006).

In OFC, the coal is burned in a composition close to pure oxygen replacing the air/coal mixture used in regular power plants. The oxygen for combustion is provided by an air separator where nitrogen is removed from the air, leaving almost pure oxygen. The coal and oxygen along with recycled CO_2 are subsequently sent into the boiler and ignited. The energy produced by the combustion process powers the steam turbines that generate electricity. The provision of 99.5% purity oxygen for the OFC results in an additional energy consumption of 0.29 kWh/kg O_2 which incurs an energy expenditure of 0.175 kWh per kWh of electrical power produced through an OFC process. Hence air separation diminishes the efficiency by almost 8% in a power plant based on OFC technology. The necessary work for compression of CO_2 to 110 bar for transport leads to a further loss of about 3.5%. Based on these considerations, total loss in efficiency is then estimated as 11–12% in power generation based on OFC based plant (Spliethoff, 2010). A simplified schematic of the OFC process is shown in Figure 1.

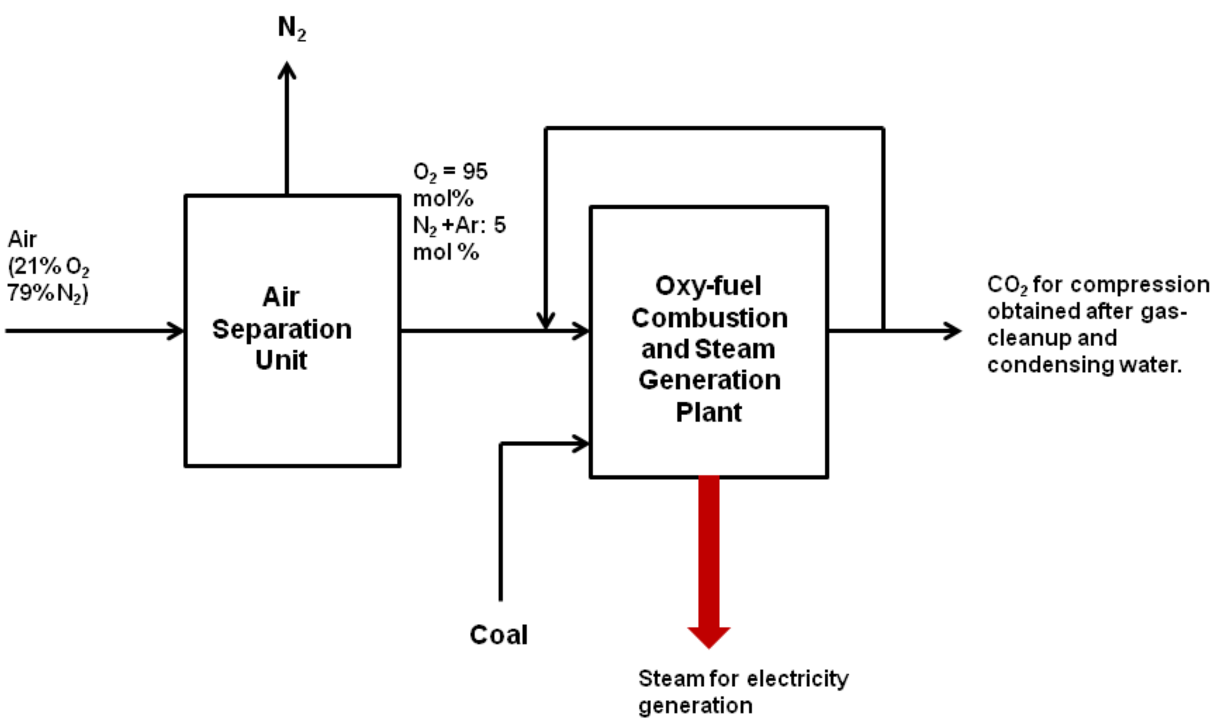

Figure 1 Simplified Schematic of an oxy-fuel combustion plant, (adapted from Riensche et al. 2011,)

To reduce the energy penalty associated with separating oxygen from air, another combustion process called Chemical-looping Combustion (CLC) is currently being investigated. CLC involves a system of two interconnected reactors with a metal oxide circulating between them. Instead of using an air separation plant, a metal oxide (Me_xO_y) supplies the required oxygen to

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burn the solid carbonaceous fuel in a reactor called the 'fuel reactor'. After losing the oxygen the reduced metal oxide (Me_xO_{y-1}) is regenerated by reaction with atmospheric air in another reactor called the 'air reactor'. In essence the metal oxide acts as an 'oxygen carrier' and helps in avoiding the associated energy penalty associated with an air separation unit. A loss of 4% in efficiency is in power generation has been estimated for power plants using the CLC technology (Epple, 2009). A simplified schematic of the CLC process is shown in Figure 2. Both CLC (presently in the industrial pilot-scale demonstration stage) and OFC (in the industrial pilot-scale stage) exhibit promise to cut down the cost of carbon capture significantly. The Institute of Clean and Secure Energy at the University of Utah is actively pursuing research interest in OFC and CLC technologies through its research program on clean and secure energy from coal (Sarofim et al., 2011, Wendt et al., 2012).

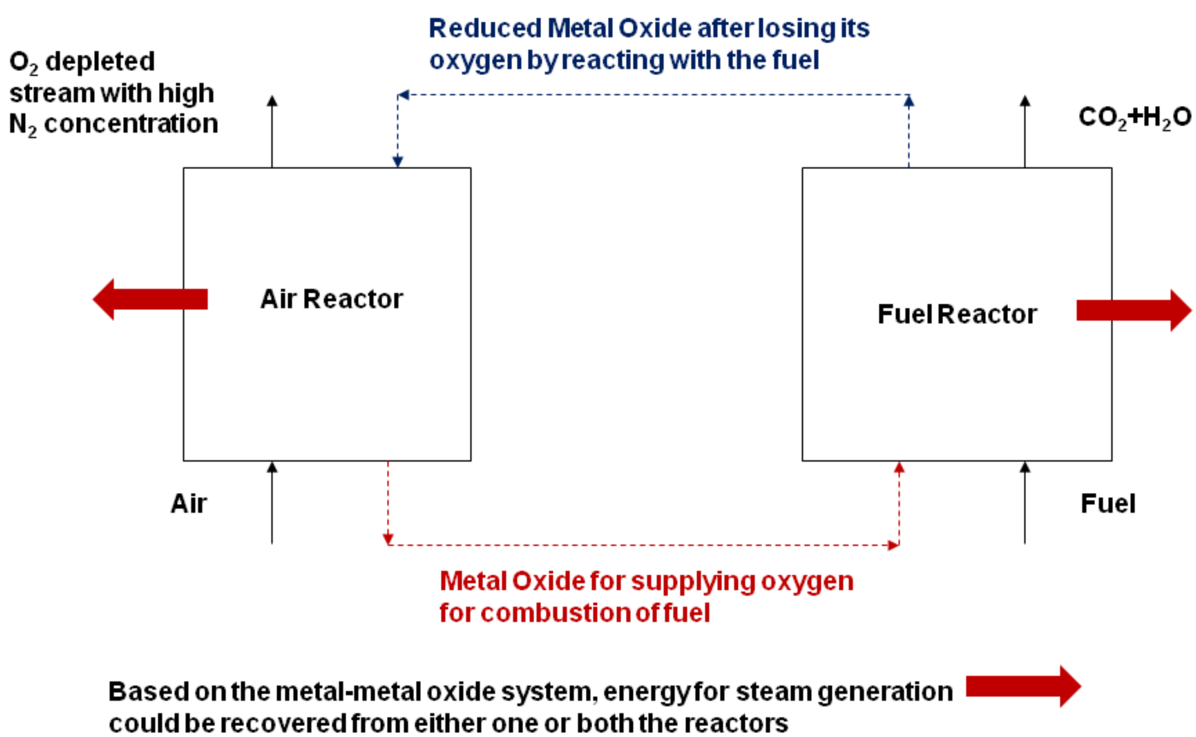

Figure 2 Simplified schematic of a chemical-looping combustion process (Adapted from Hossain and De Lasa, 2008)

According to Newell (2011), markets for energy technologies have usually emerged due to one of the three reasons. These factors also come into play when energy technologies for fossil fuels addressing carbon capture e.g. OFC and CLC are being analyzed:

1. Prices of conventional resources rise as a result of rising demand and stagnant or falling supply or production capacity.
2. Technological possibilities arise that more effectively meet energy demands
3. The government imposes new policies and regulations that affect market conditions.

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OFC and CLC have the potential to revolutionize the coal-fired power plant industry. It has been difficult for recent innovations in coal-fired power plant technology (pertaining to pollutant emission reduction and novel combustion methods) to achieve significant levels of market penetration at a faster pace. The reasons attributed are the following (Newell, 2011):

1. The rate of turnover of old coal plants and the construction of new plants in developed countries has been slow.
2. The more advanced coal-fired power plants have proven to be costly for emerging economies, where new coal-fired power plants are being built.
3. The electric power industry has perceived gasification-based combustion systems (an innovative technology incorporating 'pre-combustion' carbon capture), more costly and more risky. Novel technologies in the coal-fired power plant industry have faced significant difficulty in attracting private sector or utility investment which has rendered these technologies to be relatively untested.
4. Natural gas power plants have proven to be more advantageous than coal-fired power plants, as they can be built quickly, on a smaller scale, with a lower capital cost and have low levels of pollutant emissions. Another factor which favors natural gas power plants in the current economic scenario are low natural gas prices.

The concepts associated with OFC have been investigated since the 1970's and have been incorporated in furnaces for glass, steel and cement production. The purpose then was to provide a higher flame temperature which helped in increasing energy efficiency (Chen et al., 2012). In the case of OFC and CLC the uncertainty of performance associated with first of a kind large scale plant exists. To address the challenges associated with the technology uncertainty for OFC industrial pilot scale units, power plant manufacturers, utility providers have collaborated with industrial gas suppliers who will supply the oxygen and develop gas clean up technologies for the gaseous products of combustion. Some OFC industrial pilot-scale plants in the range of 10-40 MW_{th} have been developed (Wall, 2011) and are mentioned in Table 1. Larger-scale demonstration plants for OFC have also been planned. Vattenfall has supported a number of Swedish and German Universities (Chalmers, TU Dresden, TU Hamburg-Harburg, IVD-Stuttgart, Brandenburg Technical University) in operation of six oxy-fuel test-rigs to promote diversity in ideas towards OFC development (Vattenfall Webpage, 2012). The University of Newcastle is playing an important role in the development of Callide oxy-fuel project in Australia (ABC Webpage, 2012). Thus universities are also playing a role in the development of OFC technology through industrial-academia collaborations.

Table 1: Some examples of technological alliances in oxy-fuel combustion (Adapted from Wall, 2011)

Industrial Pilot Plant and Test Facilities	Capacity	Companies, technology providers and vendors
Callide A	30 MW_e	IHI, CS Energy, Air Liquide
Schwarze Pumpe	30 MW_{th}	Vattenfall, Alstom, Linde
Oxy-coalUK	13.3 MW_{th}	Doosan Babcock, Air Products
CIUDEN	30 MW_{th} CFB and 20 MW_{th} PC	Endesa, Foster Wheeler, Praxair, Air Liquide, Leni Gas and Oil

CFB: Circulating Fluidized Bed

PC: Pulverized Coal

Chemical-looping combustion (CLC) pilot scale demonstrations in the 250 kW_{th} to 3 MW_{th} capacities have been constructed. Interestingly for CLC also, universities have played an important role in housing the pilot scale demonstration plants and for developing the technology in its initial phase. Notable examples in this category are Technical University of Darmstadt (1 MW_{th} scale) and Ohio State University (250 kW_{th}). The role of the industry-academia consortia approach is quite evident from the descriptions available at project webpages and literature and is mentioned in Table 2. Technological developments in OFC have been reviewed by Toftegaard et al., 2010 and Chen et al., 2012., and various facets on development of CLC processes have been discussed by Fan, 2010 and Adanez et al., 2012.

In the authors opinion the role of universities and their impact in the development of OFC and CLC technologies is an interesting area of research which may be pursued from the perspective of ‘open innovation’. The latter section of the paper is devoted to highlight contemporary literature on ‘open innovation’ which can offer guidance on potential challenges and opportunities from an academic perspective which lies ahead for the development of OFC and CLC development for fossil fuel power plants.

Table 2: Some examples of technological alliances in chemical-looping combustion (Adapted from Abdulally, 2012; Fan, 2012; INNOCUOUS, 2012)

University	Capacity or Nature of the Project	Companies, technology providers and research institutions participating
TU Darmstadt	1 MW_{th}	TU Darmstadt, Chalmers, CSIC, SINTEF, Air Liquide, Vattenfall, Alstom
Ohio State	250 kW_{th}	Babcock & Wilcox (B&W), ClearSkies, CONSOL Energy, Air Products, Shell/CRI
Chalmers and TU Vienna(under the INNOCUOUS project)	Project for Testing Fluidized Bed Reactor design and oxygen carrier particles	Shell, CSIC,VITO, Johnson Matthey, Bertsch Energy

The Concept of ‘Open Innovation’ in the context of OFC and CLC technologies:

Open Innovation is an innovation model where “firms commercialize external (as well as internal) ideas by deploying outside (as well as in-house) pathways to the market”. The idea of ‘open innovation’ contrasts with the conventional idea of companies generating their own ideas in-house that they would consequently develop, manufacture, market, distribute and service themselves and is aptly termed as ‘closed innovation’. The open innovation model imparts the capability to corporations to deal with ‘false negatives’, i.e. projects that initially lack promise but then out to be of immense value (Chesbrough, 2003). Novel carbon capture technologies like OFC and CLC are either in the industrial pilot-scale or at the industrial pilot-scale demonstration phase where they indicate promise but significant technical challenges need to be addressed before successful deployment. Hence information in the open literature regarding OFC and CLC indicates a preference of favoring collaborations between academic institutions, research organizations and industries.

From an industry's standpoint, the open innovation model facilitates co-creation of technologies through the 'coupled process'. The 'coupled process' combines the 'outside-in process' (to gain external knowledge) with the 'inside-out process' (to bring ideas to market) to facilitate the innovation process (Enkel et al., 2009). Interestingly the development of OFC and CLC technologies for solid fuels exhibits elements of collaborations with universities or research organizations. The role of organizational dynamics between industries and universities in collaborative relationships from an open innovation perspective has been recently analyzed by Perkmann and Walsh, 2007. The concept of open innovation has the following benefits and challenges from a firm's perspective as mentioned in Table 3.

Table 3: Benefits and Challenges associated with Open Innovation from a firm's perspective (Gassmann et al., 2010 and Enkel et al., 2009):

Benefits	Challenges
Acceleration in research and development activities through university-industry partnerships by enhancing 'absorptive capacity' and promoting 'outside-in innovation' processes.	Identification of right partners for the collaborative project
Provides a mechanism to reduce overcapacities, cut costs, grow through complementary assets or reduce risks	Allocation of finances and time for the open innovation project
Provides the alternative of 'probe and learn' to firms in addition to the traditional 'stage-gate process'	Higher coordination costs
Easier accessibility to diverse expertise due to globalization of R&D activities.	Management of intellectual property

An interesting aspect which may merit consideration of researchers by studying the evolution of OFC and CLC technologies as novel carbon capture technologies for coal-fired power plants is the impact of partner heterogeneity on the collaboration as they evolve. It may be possible that cross-industry innovation may result in significant advances in these technologies in the future. These effects have recently been analyzed by Enkel and Gassmann (2010) for industries catering to the automotive, packaging, textile, sport, aircraft, chemical sectors.

Analyzing OFC and CLC as emergent technologies from the lens of literature in technology diffusion:

The current state of development of oxy-fuel and chemical-looping combustion technologies at either approximately 5% or 0.1% of the scale of a demonstration phase coal-fired power plant

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(assumed to be a 1000 MW_{th} capacity) also invites interest of studying aspects pertaining to technological diffusion. Although oxy-fuel and chemical-looping are in the nascent stages of their development, the following aspects merit consideration from a financial perspective which concerns the development of energy technologies addressing the goal of CCS (Ecofin Research Foundation, 2010):

1. The importance of ‘performance guarantee’ for a CCS project utilizing fossil fuels is significant. The OFC or CLC technology has to be robust enough for the coal-fired power plant whose expected lifetime is at least 25-30 years. It has to ensure flexibility in different operating conditions. The first mover ‘power generation company’ and the ‘engineering firm’ has to risk its reputation in order to build the first facility on an industrial scale.

2. The companies backing an OFC or CLC project have to be major players in the industry. Hence corporate relationships will prove to be vital in obtaining financing for the project. It also provides confidence that the major power generation company will have the engineering expertise to execute a complex large scale project with considerable technological uncertainty.

3. The importance of achieving ‘grid parity’ through a power generation technology based on OFC or CLC in a distributed energy generation future is also vital.

Popp (2004) studied the adoption of NO_x and SO_2 pollution control technologies in fossil-fuel based power plants. Using patent data it was concluded that “the inventors respond to the environmental regulatory pressure in their own country, but not to foreign environmental regulations”. Furthermore it was identified that for the development of NO_X pollution control innovations in the United States, foreign patents served as important building blocks. It is likely that environmental regulations will play a significant role in the development of carbon capture and storage technologies. The possibility of using CO_2 as an oil-recovery agent and subsequent research in utilizing CO_2 in chemical processes mentioned in the earlier section of this paper may accelerate the development of OFC and CLC technologies. Chesbrough and Appleyard (2003) in their article comment on a fundamental change in focus from ’ownership’ to the ‘concept of openness’ for some organizations working on innovative ideas. This shift encourages reconsideration of the concept of ‘value creation’ and ‘value capture processes’ by organizations, as has been demonstrated in the information technology industry by Linux and Wikipedia. In the same article, the ‘Linus’s Law’ is mentioned which states, “Given enough eyeballs, all bugs are shallow” (i.e., easy to fix). It will be fascinating to observe if Linus’s Law will also hold true in the development of OFC and CLC as forerunners for CCUS technologies in the future facilitated by an ‘open innovation’ platform.

Conclusions:

In this paper, an attempt has been made to identify synergies between advancements in oxy-fuel combustion (OFC) and chemical-looping combustion (CLC) as carbon-capture technologies for coal combustion and contemporary management research on open innovation and technology diffusion. The evolution of these technologies is not only contingent on addressing the technical challenges associated, but also depend on adoption of environmental regulations. Hence an analysis of the literature on technological diffusion and open innovation is useful to provide guidance on the challenges associated with oxy-fuel and chemical-looping technologies in scenarios where the concept of 'open innovation' is being leveraged.

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